Analysis of the Effects of Diffuse Light on Photosynthesis and Crop Production

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Abstract

Photosynthetically active solar radiation can be either direct or diffuse. Due to atmospheric scattering, solar radiation is never fully direct. Under heavy overcast conditions however, it can be fully diffuse. Screens and glass that transform direct light into diffuse light are used under the assumption that diffuse light is more evenly distributed over the canopy, increasing crop photosynthesis rate.

The Intkam crop growth model computes leaf photosynthesis rate in 5 leaf layers, for the sunlit and shaded leaf area and for the leaf areas receiving direct and diffuse light. It integrates instantaneous leaf photosynthesis rates to the crop photosynthesis rate. Instantaneous canopy photosynthesis is used to compute the seasonal growth of organs. This process approach enables a detailed analysis of the effects of variations in natural light.

An analytical comparison was made between 100% direct and 100% diffuse light for a representative day in winter (day 24) and in summer (day 202). Sunlit leaf area is illuminated by both direct and diffuse light, whereas a shaded leaf area is illuminated by diffuse light only. These components vary within and among leaf layers, and were all quantified. On both days, a higher instantaneous crop photosynthesis was computed under fully diffuse light than under fully direct light. This difference is caused by the more homogeneous distribution of diffuse light than direct light at a certain canopy depth, in combination with a declining response to increasing light intensities of the photosynthesis rate.

Experiments with three types of diffuse glass and a whitewash were conducted in 2011. Light scattering of the glass (haze) varied from 45-71%, with at least the same transmission as the reference. Tomato production under diffuse glass was increased by 8-11% in early June, and was maintained to November. The Intkam model simulated approximately the same relative seasonal production increases under diffuse glass.

INTRODUCTION

Solar energy drives photosynthesis, crop growth and production. A wide variety of methods is applied in greenhouse horticulture to maximize the amounts of available and intercepted photosynthetically active radiation (PAR) and the efficiency with which the intercepted PAR is used by the crop to synthesize carbohydrates. Methods to maximize the amount of available PAR include greenhouse constructions with low light interception; glass, foil and screens with high transmission; and assimilation lights such as SON-T and LED. Methods to maximize the fraction intercepted PAR include positioning of assimilation lights; glass, foil and screens with light diffusing properties; and increase of the leaf area index. Methods to increase the efficiency with which intercepted PAR is used for CO_2 assimilation include optimization of other environmental variables (especially the CO_2 concentration).

Radiation can be either direct or diffuse. Direct radiation comes from only one direction, whereas diffuse radiation spreads in all directions (Goudriaan and van Laar,

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1994). Solar radiation is direct before entering the atmosphere, where it is partially or completely scattered by air particles, including water droplets in clouds. Heavy overcast conditions may result in fully diffuse radiation, whereas fully direct light is not possible due to atmospheric scattering. Glass, foil and screens with diffusing properties alter direct light in diffuse light. The associated reduction in transmission can be corrected by using a coating.

The reason to increase the fraction diffuse light is the more even distribution of diffuse light over the total leaf area. This has resulted in remarkable increases in production, of up to 10% in cucumber (Dueck et al., 2009) and tomato (Dueck et al., 2012), and 9% for chrysanthemum (Markvart et al., 2010). The response to light directionality differs for the leaf and canopy levels (Brodersen et al., 2008).

This article provides a detailed explanation of the distribution of PAR over the canopy and the consequences for instantaneous and seasonal photosynthesis.

MATERIALS AND METHODS

Model

The theory on light interception by a crop has been elaborately described by Goudriaan and van Laar (1994). Global radiation is partly reflected and absorbed by the greenhouse construction; the remainder is transmitted. Typical transmission values are 65-75%. Direct and diffuse components of the photosynthetically active radiation (PAR), fractions sunlit and shaded leaf area, leaf reflectance and absorption and soil reflectance are elements in the computation of the instantaneous gross photosynthesis rate at a specific canopy depth. The Intkam crop growth model (e.g., Elings and de Visser, 2009) computes leaf photosynthesis rate in 5 leaf layers, for the sunlit and shaded leaf area. The computation of the photosynthesis rate is based on the biochemical Farquhar-von Caemmerer-Berry model (Farquhar et al., 1980; Qian et al., 2012). Sunlit leaf area receives both direct and diffuse light, and shaded leaf area receives only diffuse light. The model applies a 3-point Gaussian integration over leaf angle (Goudriaan, 1986) to obtain the instantaneous photosynthesis rate of sunlit leaf area. It integrates instantaneous leaf photosynthesis rates of sunlit and shaded leaf area to the photosynthesis rate of that leaf layer, on the basis of the fractions sunlit and shaded leaf area, and their respective instantaneous photosynthesis rates. Instantaneous crop photosynthesis rate is obtained by applying a 5-point Gaussian integration over LAI (Goudriaan, 1986). The five Gaussian depths are at 5, 23, 50, 77 and 95% of total LAI. Instantaneous crop photosynthesis is computed at 5-60 minutes time intervals, depending on the availability of environmental information, and accumulated to daily crop photosynthesis rate. After accounting for maintenance and growth respiration, and taking organ sink strengths into account, daily organ rates are obtained. Over time, this leads to computation of seasonal organ growth. This process approach enables a detailed analysis of the effects of variations in natural light.

Case Studies

Simulation studies were performed for a representative Dutch climate, which was characterized by a representative distribution of direct and diffuse light. The fractions direct and diffuse light were alternately set to 100% on days 24, a winter day with a low solar position, and 202, a summer day with a high solar position, to compare and analyse the effects of these light profiles on leaf and canopy photosynthesis. Solar position varies over the year, and within a day, which influences the penetration of light in the canopy. A leaf area index (LAI) of 7 m^2 m^{-2} was assumed at days 24 and 202 to ensure complete light interception. In reality, LAI is often lower and light interception incomplete.

Experiments

Crop performance under diffuse glass with three haze factors was compared to that under standard greenhouse glass in compartments of 144 m^2 each from December

16th 2010 to November 15th 2011 at the Wageningen UR experimental glasshouse facilities in Bleiswijk, The Netherlands (Dueck et al., 2012). The characteristics of the control and the diffuse glass types (Diff45, Diff62, Diff71) are given in Table 1. Tomato plants of cultivar Komeett were grafted onto Maxifort, at a density of 2.55 plants m^{-2}. Additional auxiliary stems were retained in week 10, resulting in 3.4 stems m^{-2}. The CO_2 concentration was maintained at about 1000 ppm (max. dosing capacity 230 kg ha^{-1} h^{-1}).

The experiments were simulated on the basis of realized climate data and crop management actions. Observed and simulated productions over time are compared, and differences are explained.

RESULTS AND DISCUSSION

Case Studies

The fraction of leaves that is exposed to direct solar radiation depends on the angle of light incidence, and thus on the solar position above the horizon, which varies over the seasons and within a day (Fig. 1). The fraction sunlit leaf area at 12:00 h is 64 and 78% on day 24 and 202, respectively. The lower fraction on day 24 is due to the lower solar angle in winter and the reduced direct transmissivity of the greenhouse at lower solar angles. Values for the second leaf layer on day 24 are 11% and 30%, respectively. Early in the morning at sunrise, the fraction of sunlit leaf area is less than 1%. Sarlikioti et al. (2011) have pointed out that explicit description of the leaf angle distribution in a 3-dimensional model can substantially improve the calculation of photosynthesis rates.

Part of the direct radiation is scattered by the canopy and becomes diffuse radiation - this is called 'the diffuse component of direct light'. The intensity of the direct component of direct light does not decrease over canopy depth, whereas that of diffuse, and the diffuse component of direct light do. Figure 2 shows a slight decrease in the light intensity on the sunlit leaf area at 12:00 h on days 24 and 202, when all light entering the greenhouse is direct, due to the decrease in the intensity of the diffuse component of direct light. If all light entering the greenhouse is diffuse, then the light intensity of the sunlit leaf area decreases rapidly over canopy depth. This decrease is very similar to the one for diffuse light intensity on shaded leaves.

The average light intensity at a certain canopy depth is obtained by balancing the fractions sunlit and shaded leaf area at each canopy depth, and the light intensities of the direct and diffuse light fractions reaching these leaf area fractions. This results in approximately similar average light intensities in case of fully direct and fully diffuse light entering the greenhouse at 12:00 h on day 202 (Fig. 3). The average light intensity in the top layer is then slightly higher in case of 100% diffuse light, while the average light intensities in the other layers are slightly higher in case of 100% direct light. However, at 12:00 h on day 24, the picture is reversed: the average light intensity in the top layer is higher in case of 100% direct light, while the average light intensities in the other layers are lower in case of 100% direct light.

The same holds for the gross photosynthesis rate which decreases only marginally over canopy depth for sunlit leaf area that receives direct radiation. If all light entering the greenhouse is diffuse, then the gross photosynthesis rate at sunlit leaf area decreases rapidly over canopy depth. This decrease is similar to the one for diffuse light intensity at shaded leaf area. Also the average gross photosynthesis rate at a certain canopy depth is obtained by balancing the fractions sunlit and shaded leaf area at each canopy depth, and their respective gross photosynthesis rates. Unlike the approximately similar average light intensities in case of fully direct and fully diffuse light entering the greenhouse, this results in higher gross photosynthesis rates at all canopy depths in case of 100% diffuse light at 12:00 h on day 202 (Fig. 4). The reason for this lies in the non-linear shape of the photosynthesis light response curve, which shows a declining response to increasing light intensities, in combination with the better distribution of diffuse light at a certain canopy depth. In other words, 100 µmol direct PAR intercepted by sunlit leaf area results in a lower gross photosynthesis rate than 50 µmol diffuse PAR intercepted by sunlit leaf area and the same amount by shaded leaf area. At 12:00 h on day 24, 100% direct radiation results in a higher photosynthesis rate only in the top layer (Fig. 4).

The gross photosynthesis rates of the entire canopy is obtained through a Gaussian integration of the gross photosynthesis rates at the five canopy depths, which involves specific weighing factors. Figures 5 and 6 present the integrated values at 12:00 h on days 24 and 202 for absorbed PAR and gross photosynthesis. Direct PAR is better absorbed in the top layer on day 24, but absorption of diffuse and direct PAR show only a limited difference on day 202. However, at both days, the difference in gross photosynthesis rate is substantial at the advantage of diffuse light.

Experiments

Fresh weight production under diffuse glass was 8-11% higher than under standard glass (Table 1). This difference had already been reached by June. Botrytis infection was observed in all treatments during the last two months prior to harvest, and was highest in the control. However, the final differences in production had been realized before Botrytis became a problem and thus it is expected to have had a limited effect on the production differences (Dueck et al., 2012).

The Intkam model simulates approximately the same relative seasonal production increases under diffuse glass (Table 1). The only important difference is the fact that observed fresh production is the highest in the case of 71% haze and 82% transmission (Diff71), while the simulated fresh production is the highest in case of 62% haze and 85% transmission (Diff62). An analysis of the simulation results suggests that an increased glass transmission of 82 to 85% has a larger effect on crop growth than an increase of the haze factor from 62 to 71%. For these fractions, the larger amount of light results in a greater effect than the increased fraction diffuse light. It should be noted that under normal conditions, a substantial fraction of light is already diffuse, and that theoretically, diffuse glass is only effective under conditions of relatively large levels of direct light. The experimentally realized production of Diff62 lags behind the production of Diff71. This might have been caused by the removal of stems to manage the presence of *Botrytis*, which was not accounted for by the Intkam model.

Figure 7 shows variation over time in simulated fresh production. This is not unusual, however, and can be explained by the variation over time in solar radiation. Most of the additional simulated production under diffuse glass is obtained in the month of June. The months of April, May and June in 2011 were characterized by relatively high amounts of direct radiation that was scattered by the diffuse glass treatments. The extra growth resulted with some time delay in extra production in June. June, on the other hand, was characterized by high levels of diffuse radiation, resulting in less extra production under diffuse conditions in July, August and September. These patterns were not observed in the experiment, however, where production was more evenly distributed over the season. Apparently, other mechanisms have influenced the relation between light and crop production, and have caused a certain temporal stabilization. Crop management actions may have played a role. For example, the farmer may have varied to some extent the moment of harvest to stabilize his farm production, which is not accounted for by the model.

CONCLUSIONS

Diffuse light is more evenly distributed within a certain canopy layer than direct light, which, due to the decreasing efficiency of additional light at high light intensities, results in a higher instantaneous leaf photosynthesis rate in case of diffuse light. This mechanism results in increased seasonal photosynthesis and fresh production if diffuse glass is used in greenhouses.

ACKNOWLEDGEMENTS

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Tables

Table 1. Haze factor (%) and hemispherical transmission (%) of the glass used in the experiment.

Glass type	Haze factor (%)	Hemispherical transmission		Fresh production	
		(%)	% of control	Observed (% of control)	Simulated (% of control)
Control	0	82.7	100	100	100
Diff45	45	82.6	100	108	108
Diff62	62	85.4	103	109	112
Diff71	71	82.9	100	111	108

Figures

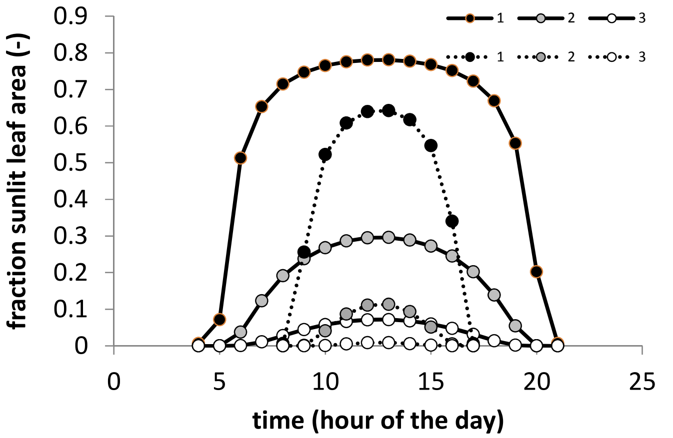

Fig. 1. Fraction sunlit leaf area at day 24 (dashed lines) and 202 (solid lines), for the three top Gaussian LAI depths.

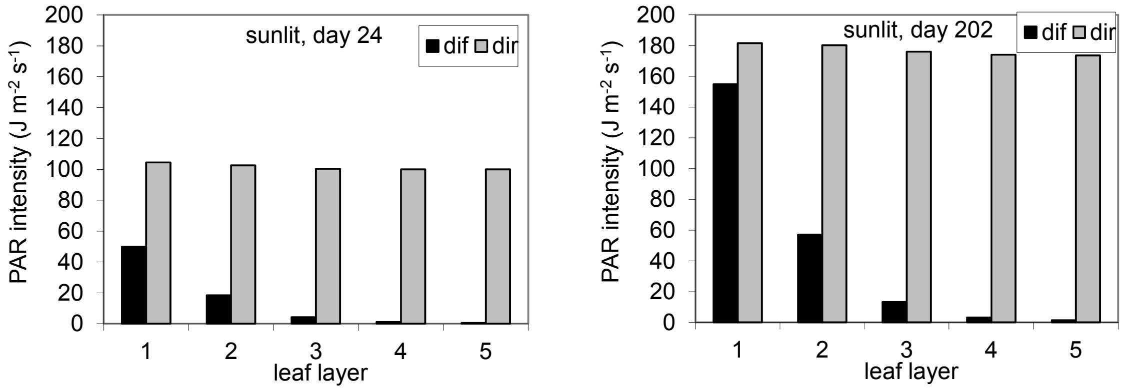

Fig. 2. Light intensity at five Gaussian canopy depths in case of 100% direct and 100% diffuse light entering the greenhouse, for sunlit leaf area, for days 24 and 202. Light intensity of diffuse light for shaded leaf area is similar to the one for sunlit leaf area.

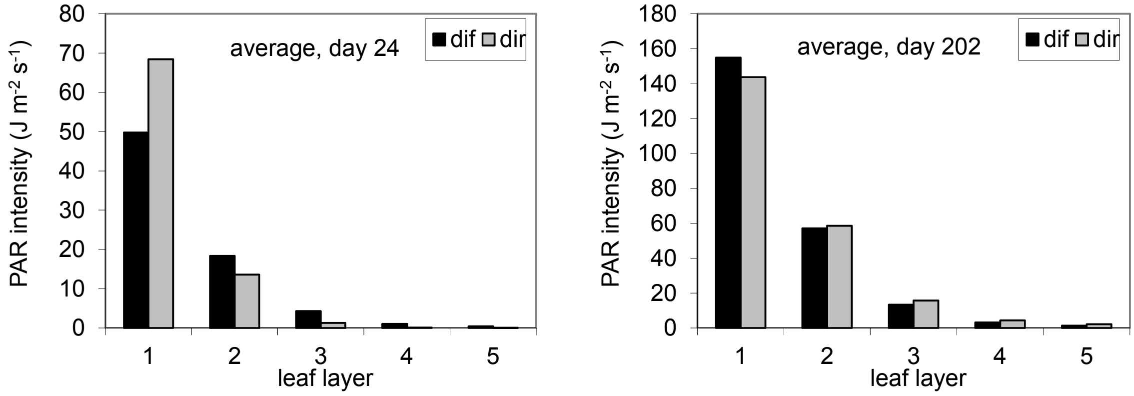

Fig. 3. Light intensity at five Gaussian canopy depths in case of 100% direct and 100% diffuse light entering the greenhouse, averaged over sunlit and shaded leaf area, for days 24 and 202.

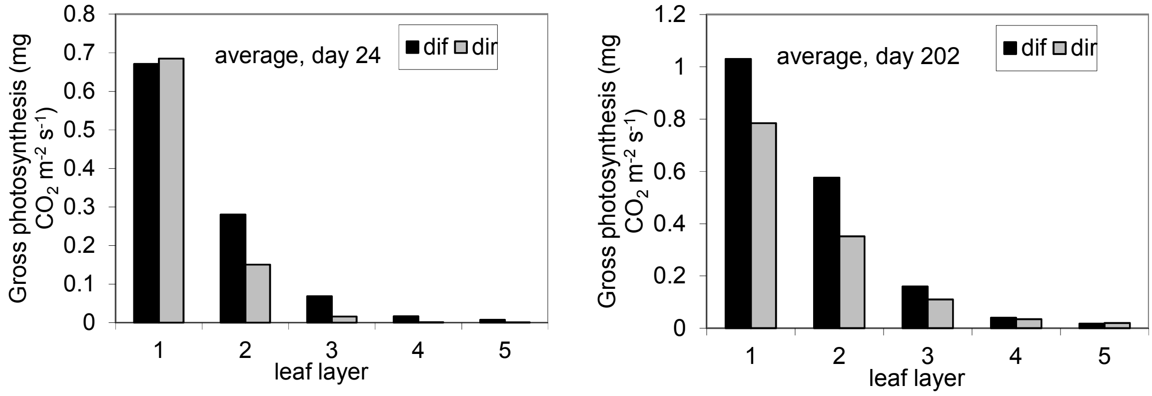

Fig. 4. Gross photosynthesis at five Gaussian canopy depths in case of 100% direct and 100% diffuse light entering the greenhouse, averaged over sunlit and shaded leaf area, at days 24 and 202.

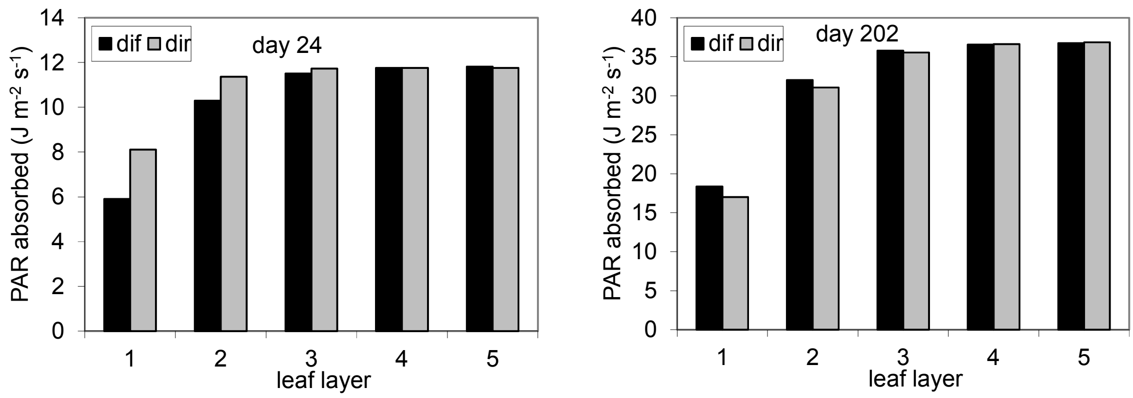

Fig. 5. Cumulative absorbed PAR over 5 Gaussian canopy depths in case of 100% direct and 100% diffuse light entering the greenhouse, at days 24 and 202.

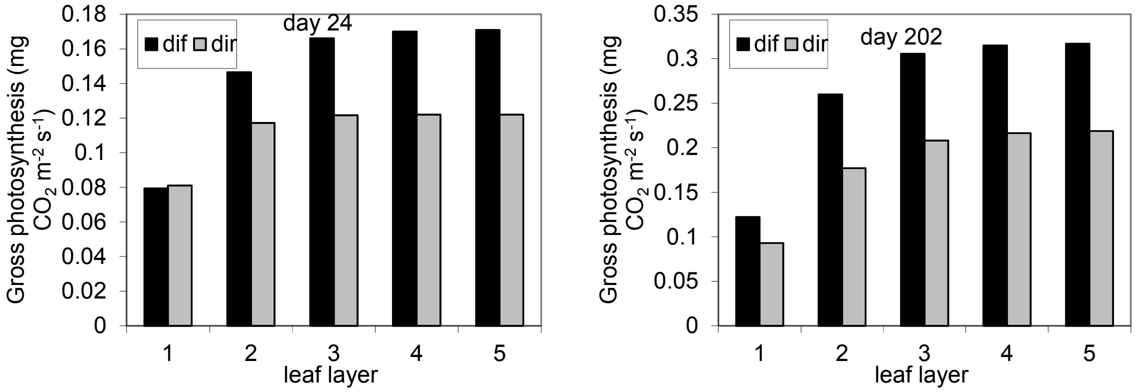

Fig. 6. Cumulative gross photosynthesis over 5 Gaussian canopy depths in case of 100% direct and 100% diffuse light entering the greenhouse, at days 24 and 202.

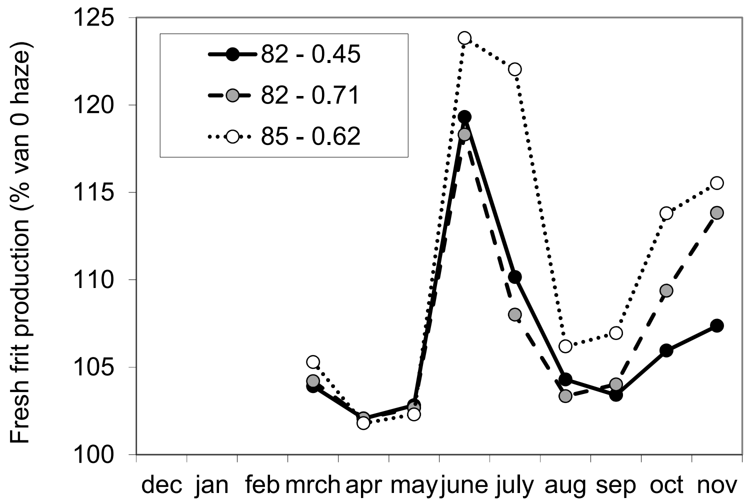

Fig. 7. Simulated monthly fresh production for the experimental treatments. The fresh production of the reference (standard clear glass) is set to 100%.